Verification: Constructive and Destructive Full Duplex Relays

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ABSTRACT

With recent advances in in-band full duplex techniques, full duplex capable relays have been shown feasible in many recent works. Instead of generating data itself to transmit, a full duplex relay can forward the received signal while receiving it. It also has the opportunity to properly modify the signal before forwarding it, which has been explored to enable constructive and destructive full duplex relaying recently. With these designs, the signal through the full duplex relay could constructively or destructively add up with the signal from the direct link at the receiver side. As a result, the received signal power may be boosted or greatly reduced, compared with direct forwarding. In this paper, we do detailed analysis on whether such constructive and destructive full duplex relays are possible. We find that for OFDM signals, such relays can not be achieved if the additional latency of the relayed path is more than one sample time than the direct link. Our analysis and results challenge the assumptions on the relay latency requirements of previous works to realize such systems.

CCS CONCEPTS

• **Networks** → *Wireless access networks*.

KEYWORDS

Full duplex relay; Full duplex; Cooperative relay

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Figure 1: A destructive full duplex relay R can potentially nullify the direct link signal from node A to node B . As a result, B may not hear this transmission.

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1 INTRODUCTION

Full duplex relays have been shown possible in many recent works. A full duplex relay can forward the received signal while receiving it at the same time and in the same frequency band, as the relay is free of its own interference by applying self interference cancellation. Similar to traditional half duplex relays, full duplex relays have been used to enlarge communication range and converge, but utilizing less wireless resources (e.g., frequency, time) [1, 8, 16].

A full duplex relay also has the opportunity to modify the signal before forwarding it. Recently, a system called FastForward [3] proposes that by applying appropriate filters at the full duplex relay, the signal from the relay path could *constructively* add up with the signal from the direct link. As a result, the signal strength at the receiver could be much higher than that with simple amplify-and-forward full duplex relaying. Following the same designs, IC2 [14] shows that *destructive* relaying is also possible. Specifically, as shown in Fig. 1, the destructive full duplex relay R could properly change the signal from node A before forwarding. As a result, the signals from the direct link and the relayed path could *nullify* each other at node B . B may not hear the transmission due to this nullification.

We find that such destructive relaying is specially interesting as there are many potential applications with destructive

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relays. **Hidden terminal problem.** When A transmits packets to some other nodes, B will observe interference from these transmissions if they are in the same collision domain. Another node unaware of these transmissions may try to transmit to B at the same time, resulting in collisions. Now with the nullification ability of R , A can transmit as usual while B can receive its intended streams as if there was no interference. **Scaling full duplex multiuser MIMO.** Imagine R is an access point (AP). Suppose A wants to do uplink transmissions to R , while R has some data for the downlink client B . Even with full duplex capability, R could not initialize simultaneous downlink transmissions since B is experiencing interference caused by A , or uplink-downlink interference [14, 25]. If R can nullify the direct link signal from A to B by destructive relaying, R may superimpose its data intended for B on top of the relayed stream. As a result, R services both uplink and downlink clients simultaneously, fully utilizing its full duplex capability while clients remain half duplex. Note that the solution may scale to multiuser case if R has more than one antenna. **Cognitive radios.** Assume B is the primary receiver in cognitive radio settings, R can be treated as a protector: it can nullify transmissions from secondary users like A . In these applications, it is especially interesting to note that R is transparent to the system, no major changes¹ are needed for nodes A or B .

On the other side, such a system may bring new security challenges. **Denial-of-service (DoS) attack.** A destructive full duplex relay could disconnect specific receivers from the network by nullifying the signals. Compared with jamming based DoS attacks, nullification is more effective and harder to be detected since it is highly targeted. **Takeover attack.** Imagine node A is a GPS satellite and B the client receiver, the relay could initialize a seamless lock takeover attack to take control of the victim receiver. As a result, the receiver locks on to the relay, instead of the satellite. Such attacks could be more effective by nullifying the legitimate signals from the satellite, even defeating the state-of-the-art spoofing resistant GPS receiver designs [22], as mentioned by the authors.

Wireless channel is a common resource that is shared by all users. If a wireless node transmits a signal omnidirectionally, it is likely that all other nodes within the communication range will hear the transmission. However, as can be seen from above examples, destructive full duplex relays have the ability to change the *sharing nature* of the wireless medium. We think such a system may have wide impacts on research areas including MAC layer protocols, interference management, wireless security, etc. This leads to the key question we ask in this paper: *Is it even possible to realize such constructive and destructive full duplex relays?*

In this paper, we conduct detailed analysis and develop conditions to realize such systems. Specifically, we find that for OFDM signals, such relays cannot be achieved if the additional latency of the relay path is more than one sample time than the direct link. ***This is in contrast to works that consider cyclic prefix (CP) length of OFDM signals as the timing constraint*** [3, 14]. Our paper challenges such assumptions. This far stricter requirement implies that the constructive or destructive relaying gains will be limited in most cases.

Overall, this paper makes the following contribution:

- We analyze the conditions under which constructive or destructive relaying is possible. We find that such conditions are hard to realize in practice, unlike what is presented in existing literature.

2 BACKGROUND

In this section, we introduce some background knowledge needed for our analysis.

2.1 System model

As shown in Fig. 1, assume the channels from A to B , A to R and R to B are h_{ab} , h_{ar} and h_{rb} , respectively. Assume a filter f_r can be applied at R before forwarding. Node B will receive

$$y(n) = y_{direct}(n) + y_{relay}(n), \quad (1)$$

where

$$y_{direct}(n) = h_{ab} * x(n), \quad (2)$$

$$y_{relay}(n) = h_{ar} * \delta(n - \Delta d) * f_r * h_{rb} * x(n). \quad (3)$$

Here $*$ denotes convolution, $x(n)$ is the transmitted signal by node A , and $\Delta d > 0$ is the delay incurred at the relay R . Note that the extra delay is inevitable at relays due to sampling, processing, etc.

Noise is omitted here for simplicity. Noise needs to be considered carefully when setting power amplification for the relay, which has been discussed and addressed in previous works [3, 7, 8, 14].

2.2 Constructive and destructive addition

Given a sample x , when adding two copies of x with phase shift, the power after this combination varies depending on the relative phase of the two copies. Mathematically, the resulting power is given by

$$P_x = \left| x e^{j\theta_1} + x e^{j\theta_2} \right|^2. \quad (4)$$

Depending on the difference between θ_1 and θ_2 , P_x can ranges from 0 (perfect destructive addition) to $4|x|^2$ (perfect constructive addition). Fig. 2 shows the resulting power with different phase offset ($|\theta_1 - \theta_2|$), compared with the baseline power $|x|^2$.

¹Cooperation may be needed such as CSI sharing.

Figure 2: Power gains when combining two copies of the same sample with varying phase offsets.

It can be shown that with θ_1 and θ_2 being uniformly distributed variables within range 0 to 2π , the expectation $\mathbb{E}(P_x) = 2|x|^2$.

2.3 FastForward and IC2

Observing that samples (subcarriers) from the direct link and the relayed link may add up destructively naturally if not controlled, FastForward [3] is proposed to achieve constructive relaying by avoiding destructive additions.

For the topology shown in Fig. 1, the expected received power at B is the sum of the direct link power and the relayed power. In FastForward, the authors propose that by setting a proper filter f_r , constructive addition can be achieved at the receiver side. This means that the received power is larger than simply adding up the power of the two paths. Mathematically, with FastForward, we are expecting

$$\mathbb{E}(\|y\|^2) > \mathbb{E}(\|y_{\text{direct}}\|^2) + \mathbb{E}(\|y_{\text{relay}}\|^2). \quad (5)$$

If perfect constructive addition is achieved, and assuming the direct link and the relayed link have the same signal strength at the receiver, we are expecting 6 dB SNR gain over the direct link only transmissions, namely,

$$\mathbb{E}(\|y\|^2) = 4\mathbb{E}(\|y_{\text{direct}}\|^2). \quad (6)$$

Similarly, the authors in IC2 [14] attempt to let the two paths nullify each other with properly set f_r . As a result, the received power is much smaller than the direct link signal, or

$$\mathbb{E}(\|y\|^2) \ll \mathbb{E}(\|y_{\text{direct}}\|^2). \quad (7)$$

With perfect nullification, signals from the direct link and relayed link will nullify each other such that the receiver does not hear from the transmissions.

2.4 OFDM and cyclic prefix

OFDM is widely used in systems like WiFi and LTE. FastForward and IC2 work with OFDM signals. CP is introduced mainly to avoid inter-symbol interference. Specifically, the

tail (8 or 16 samples in WiFi) of an OFDM symbol is usually copied and prepended to the front of the symbol. The CP length ratio (CP length over symbol length) is usually determined by the maximum expected delay spread, and is kept low to avoid large overhead.

A major design goal of FastForward is to minimize the latency incurred at the relay, such that the relayed signal can fall within the CP. The authors in [3] indicate that the constructive relaying can be achieved as long as this goal is met, namely, the relayed signal arrives within the CP length of OFDM symbols. The follow up work called IC2 [14] also considers CP length as the relay latency requirement.

3 ANALYSIS

In this section, we provide a detailed analysis on conditions needed to achieve constructive or destructive relaying. For ease of explanations, we focus on constructive relays, yet a similar analysis can be performed on the destructive relay case.

3.1 Observations

In this part, we make several observations.

OBSERVATION 3.1. *An FIR filter f_r can **not** be practically set such that $\delta(n - \Delta d) * f_r = \delta(n)$, where $\Delta d > 0$.*

This is because f_r has to be a causal filter, which means that it can not undo the delay already incurred, or predict future samples.

OBSERVATION 3.2. *Let f be a causal filter. Given $S_1 = [s_1, s_2, \dots, s_n]$ and $S_2 = [s_0, s_1, \dots, s_{n-1}]$, where s_i are independent and zero-mean Gaussian distributed variables, we have*

$$\mathbb{E}(\|S_1 + f * S_2\|^2) = \mathbb{E}(\|S_1\|^2) + \mathbb{E}(\|f * S_2\|^2). \quad (8)$$

Based on properties of independent Gaussian distributed random variables [27], and the fact that s_i and s_{i+1} are independent and zero-mean Gaussian variables, we have

$$\mathbb{E}(\|S_1 + S_2\|^2) = \mathbb{E}(\|S_1\|^2) + \mathbb{E}(\|S_2\|^2). \quad (9)$$

With f applied to S_2 , based on Obs. 3.1, f can not be set such that S_1 and S_2 are aligned. In other words, each i -th coordinate of $f * S_2$ is a linear combination of $\{s_0, s_1, \dots, s_{i-1}\}$, thus independent from s_i . By induction, Eq. 8 holds.

OBSERVATION 3.3. *Samples (real and imaginary parts separately) of OFDM signals tend to follow independent zero-mean Gaussian distribution.*

It is well known that the n -th sample of an N -subcarrier OFDM symbol can be expressed as:

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) e^{-j \frac{2\pi k n}{N}}, \quad (10)$$

Figure 3: Samples (real and imaginary part separately) of OFDM signals largely matches normal distribution.

where $X(k)$ is the modulated data on the k -th subcarrier, and is assumed to be zero-mean independent and identically distributed (i.i.d.). This is a reasonable assumption in reality as scramblers are usually employed to randomize the input data in practice. When number of subcarriers of OFDM signals is large, it has been shown that the resulting time domain samples tend to be independent Gaussian random variables, by invoking the central limit theorem [18, 23].

Fig. 3 shows the distribution of samples (real part²) in 64-subcarrier OFDM symbols with QPSK and QAM64 modulation schemes, respectively. The signal contains 1000 symbols. As can be seen, both of them largely match the normal distribution (shown in red dashed lines).

As an alternative high-level understanding of the independence argument, given the input data is random, since one can not use previous time domain samples to predict future samples within a symbol in general (otherwise there is no need to transmit the future samples), the time domain samples can be treated as independent.

OBSERVATION 3.4. *If constructive relaying is achieved in the frequency domain, then it is also achieved in the time domain, and vice versa.*

The target of constructive relaying is to increase the signal power. Signal power is the same whether looking in the frequency domain or time domain. Note that with OFDM, power redistribution among subcarriers such that some subcarriers have higher power and others have lower power does not lead to total power increase.

OBSERVATION 3.5. *The relayed signal is likely to arrive later than the direct link signal in practice.*

Notice that $D_{ar} + D_{rb} \geq D_{ab}$, where D_{ij} is the distance between node i and node j . If all links have line of sight (LoS)

²Imaginary part gives very similar distribution results.

paths, then it takes more time for the signal to travel in the relayed link. Additionally, recall that the latency at the relay Δd is positive. Together it is likely that the relayed signal arrives later than the direct link signal at the receiver.

Definition (τ): τ is defined as the time that the relayed signal lags behind the direct signal at the receiver. The arriving time of a signal is determined by the first tap (fastest tap) of the signal. In other words, in the case of multi-tap channels, τ equals to the time difference between the first tap of the relayed signal and the first tap of the direct link signal. For simplicity, we use sample time as the unit of τ and $\tau \in \mathbb{N}$. Note that if the absolute time of τ is in between of two samples, it translates to phase shift of the signals. Also notice that τ is still possible to be zero or negative if the direct link has a larger propagation delay possibly due to the lack of LoS path.

OBSERVATION 3.6. *Single-tap channel is the most favorable condition for the relayed signal.*

Given single-tap channel for the relayed signal, multi-tap channel can be artificially created with the filter within the relay, if multi-tap channel is more favorable. In other words, multipath in h_{ar} and h_{rb} have the same effects as setting f_r in the relay. Multi-tap channel for the relayed signal is not helpful in achieving full duplex constructive or destructive relaying. So we may treat the combined channel of the relay link as f_r for simplicity, which includes the effects of h_{ar} and h_{rb} as well as the applied filter.

3.2 Claims

In this part, we make the following claims based on the observations we have in the previous section.

CLAIM 3.1. *For single-tap direct link channel, constructive relaying can **not** be achieved if $\tau \geq 1$ sample time.*

Single-tap channel refers to channel vectors that have only one non-zero value. Without loss of generality, we may normalize $h_{ab} = 1$. Based on Obs. 3.6, the combined channel of the relay link can be represented as f_r . As a result, the receiver will observe

$$y_{direct}(n) = x(n), \quad (11)$$

$$y_{relay}(n) = f_r * x(n - \tau). \quad (12)$$

Based on Obs. 3.3, $x(n)$ can be viewed as an independent and zero-mean Gaussian distributed sequence. Based on Obs. 3.2 and the fact that $\tau \geq 1$ sample, we have

$$\mathbb{E}(\|y_{direct} + y_{relay}\|^2) = \mathbb{E}(\|y_{direct}\|^2) + \mathbb{E}(\|y_{relay}\|^2), \quad (13)$$

for $\forall f_r$. Comparing with the constructive addition target specified in Eq. 5, together with Obs. 3.4, we see that constructive relaying can **not** be achieved in this case.

Figure 4: Example of signal nullification due to out-of-phase when $\tau < 1$.

One may have concerns on the role of CP in helping provide such alignment. In fact, given $S_1 = [s_k, \dots, s_n, s_1, \dots, s_n]$ and $S_2 = [0, s_k, \dots, s_n, s_1, \dots, s_{n-1}]$, where s_i are samples in an OFDM symbol, and samples from s_k to s_n are used as the CP. It is not hard to see that we may keep doing right shift operations (delays) to S_2 until the CP of S_2 are aligned with the symbol tail of S_1 .

However, this method can only achieve constructive addition to the tail of a symbol (s_k to s_n). Unless CP length ratio is larger or equal to 1 (which is usually not a wise option in practice due to large overhead), this method will cause inter-symbol interference. This is because the total shift operations needed is larger than the CP length, leading the tail of S_2 to be leaked beyond the CP tolerance of its next symbol. As such, this is not the target of this paper or [3, 14].

CLAIM 3.2. *For single-tap direct link channel, constructive relaying may be achieved if $\tau < 1$ sample time.*

With $0 \leq \tau < 1$ sample time, the delay is captured by the channel as phase rotations. To achieve constructive relaying, we may simply rotate the signal before forwarding. This can be done in digital domain by multiplying the signal with $e^{j\theta}$. Or it can be done in analog domain by properly delaying the signal such that the two copies of the signal are $k\lambda/2$ apart, where $k = 1, 3, 5, \dots$ and λ is the wavelength of the signal. We notice that this property has also been explored in full duplex designs to achieve antenna cancellation [9].

Fig. 4 illustrates an example of destructive addition in this case. As can be seen, the signals can nullify each other except the sample boundary. Depending on the sampling time and duration, the receiver may not hear the transmission or only observe small interference.

For $\tau < 0$, we may easily delay the relayed signal with f_r such that $\tau = 0$, and the above discussion applies.

Next, we discuss the cases where the direct link is multi-tap channel.

CLAIM 3.3. *Generally, constructive relaying can **not** be achieved if the relayed signal arrives later than the last tap of the direct link channel.*

For multi-tap direct link channel, the direct link signal can be seen as multiple single-tap channel signals. As all of these separated signals fulfill $\tau \geq 1$ sample, based on Claim 3.1, we see that constructive relaying can not be achieved in this case.

Our Claim 3.3 challenges previous assumptions that CP length is the timing constraint for OFDM signals to achieve constructive and destructive relaying. Specifically, we show that constructive relaying is not necessarily achievable even when the CP timing constraint is met.

CLAIM 3.4. *Generally, **partial** constructive relaying may be achieved if the relayed signal arrives within the delay spread of the direct link channel.*

Arriving within the delay spread means that the relayed signal arrives later than the first tap of the direct link channel and earlier than the last tap. Similar to the reasoning of Claim 3.3, the direct link signal can be seen as multiple single-tap channel signals. As some of these separated signals fulfill $\tau < 1$ sample, based on Claim 3.2, we see that constructive relaying may be achieved for these taps and thus partial constructive relaying.

Note that in practice, multipath taps are usually weaker than LoS paths. As a result, the partial constructive relaying may yield limited gain in practice. For destructive relaying, as the taps of the direct link arriving earlier than the relayed link is untouched, the nullification may only see small power reduction by cancelling only multipath taps. For example, given a two-tap direct link channel, and each tap has the same power, only 3 dB power reduction is expected even if the second tap can be fully nullified. In other words, the far stricter requirement on relaying path latency implies that the constructive or destructive relaying gains will be limited in most cases, if any.

CLAIM 3.5. *Generally, constructive relaying may be achieved if $\tau < 1$ **sample** time.*

Claim 3.5 follows from the reasoning of Claim 3.2 and Claim 3.4.

In summary, Claim 3.2, 3.4 and 3.5 give different timing requirements needed to achieve constructive or destructive relaying under different conditions. All of these are different from the CP length timing constraint, which is believed to be the timing constraint in previous works [3, 14]. Generally, a much stricter timing constraint on the relayed signal is needed to achieve constructive or destructive relaying.

3.3 Other facts

In this part, we provide some additional facts that we think are helpful to understand the problem.

- 1) Why can't we extract each subcarrier and properly shift each of them separately?

The relay does not know the data being transmitted beforehand. It gets to know samples one after another at real time. To extract each subcarrier, the relay needs to do operations like Fourier transform. This means that the relay has to wait until a symbol is fully received. Clearly, the extra large latency incurred (1 *symbol* time) makes this unfeasible in practice. This has already been noticed in [3].

- 2) Power may be redistributed across subcarriers when constructive relaying is *unachievable*.

It is well known that time domain delay translates to linear phase shift to subcarriers in the frequency domain. Specifically, for the k -th subcarrier,

$$x(n - \tau) \xrightarrow{\mathcal{F}} e^{-j\frac{2\pi k\tau}{N}} X(k). \quad (14)$$

This phase shift at subcarriers of the relayed signal may lead to natural constructive addition with the direct link signal on specific subcarriers. As a result, the power of these subcarriers may be boosted. However, with $\tau \geq 1$, it can be shown that some other subcarriers will observe a lower power at the same time due to natural destructive addition. In other words, the power boost on specific subcarriers is at the cost of lower power on other subcarriers. The total power of the combined signal remains unchanged as we already shown in Eq. 13.

4 EXPERIMENT

In this section, we do experiments mainly to see the effects of latency of the relayed signal. Software defined radios USRP N210 equipped with WBX daughterboards are used for evaluations. We use 2 GHz as the carrier frequency and the sampling rate is set to 10 MHz in our experiments. The packets used for transmissions are generated with the GNURadio IEEE 802.11 implementation introduced by Bloessl et al. [6]. QAM16 is used as the modulation scheme.

Due to hardware limitations, we observe up to 10 ms latency introduced by the relay USRP when forwarding. We bypass this issue with tricks as detailed in the following sections.

4.1 Constructive and destructive addition v.s. latency of the relayed signal

The purpose of this experiment is to verify our Claim 3.1 and Claim 3.2. In this experiment, three USRPs are used to act as transmitter, relay and receiver. Due to the large forwarding latency, we directly give the samples to the relay node. The transmitter node and relay node are synchronized in both time and frequency. We let the two nodes to start to transmit at exactly the same time. A variable length cable is connected to the transmit chain of the relay node. By controlling the cable length, the relayed signal arrives later than the direct link signal by different amount of time (τ) due to varying

(a) Nullification performance. (b) Constructive addition.

Figure 5: Performance of destructive and constructive relaying with varying relative latency τ (100 ns corresponds to 1 sample time).

propagation delays. Power is carefully controlled such that the signal from both paths have similar power at the receiver. Both the transmitter and the relay are directly connected to the receiver by cables.

Fig. 5 shows the results of destructive and constructive addition at the receiver with varying latency τ introduced. τ is inferred by calculating the extra cable length introduced divide by the speed of light. With 10 MHz sampling rate, 100 ns corresponds to 1 sample time. We try all possible phase at the relay node to get the best performance of nullification or addition. As can be seen from Fig. 5a, when there is no additional latency, we observe a 20 dB power reduction from the direct link only case. Similarly, Fig. 5b shows a 6 dB power boost when $\tau = 0$, which means perfect constructive relay is achieved (see Eq. 6).

However, with larger delays introduced, the performance of both constructive and destructive relaying degrades quickly. For example, with $\tau = 20$ ns, only 10 dB nullification is achieved. As the latency goes beyond 1 sample time, nullification is no longer achievable. Similarly, as shown in Fig. 5b, the performance of constructive addition also suffers with larger τ . At 1 sample time (100 ns), we still observe 4 dB gain (instead of 3 dB). We think this is because of the sampling offset between the transmit/relay and the receiver. As a result, the received channel may not be perfect single tap. We see that no obvious constructive addition is achieved beyond 130 ns (1.3 sample time).

4.2 Power redistribution across subcarriers

To get a better understanding of the performance when the relative latency τ is large, we add an artificial two-sample delay in the digital domain to the relay node.

Figure 6: Power of the received signal is redistributed across subcarriers with varying initial phase applied to the relay node. Total signal power remains similar.

Fig. 6a shows the SNR of each subcarrier of the received signal with varying initial phase applied to the relay node. As can be seen, changing phase of the relayed signal can only result in power redistribution across subcarriers. This result justifies our analysis made in Sec. 3.3.

We also calculate the average power for each phase and find that the power variance is within 1 dB, as shown in Fig. 6b. The small variance is mainly caused by the guard bands of WiFi signals. When the nullified subcarriers are located in the guard bands, which happens when phase is set to around 180 degrees in this experiment, a slightly higher power is observed. Notice that there is only about 3 dB gain even in this case, which means no constructive addition is achieved (which should give 6 dB gain in the best case). These results again justify our Claim 3.1.

5 IMPLICATIONS

From our analysis and experimental results, we see that the latency requirement on the relayed link for achieving constructive or destructive relaying is more strict than assumed in previous works. Specifically, falling within the CP length is just the first step, the relayed link needs to arrive approximately the same time as the direct link signal to achieve reasonable amount of constructive or destructive addition.

We find that in FastForward [3], there is no direct experimental proof showing that constructive addition is achieved nor its performance in reality. Specifically, we were expecting to see the results on the SNR improvement with and without the constructive filtering. The most relevant result is figure 17 in [3], where the authors compared throughput performance of FastForward and amplify-only full duplex relays, but at the same time the authors also disabled the proposed amplification setting module, and the authors themselves state that the performance gain comes from proper

amplification, without mentioning the constructive filtering. All other related results (figures 12-15 in [3]) are throughput comparison among FastForward, half duplex relays and without relays. Throughput gain of full duplex relaying over half duplex relaying is expected even without the constructive filtering, as full duplex relays do not need an extra time slot to forward the packet, which is needed for half duplex relays.

In fact, based on our Obs. 3.4, **partial** constructive addition **can** be achieved when the relayed signal arrives within the delay spread of the direct link. So there may be some small SNR gain observed especially in multipath rich environment where multipath signals are strong.

IC2 [14] is a follow up work of FastForward. The experiments are not real time, as the authors in [14] state that the functionality of the destructive filtering in *emulated* in the software. So there is no experimental proof that destructive relaying is achievable.

It must be noted that while we are challenging the timing requirements necessary for constructive and destructive relaying, this paper does **not** question other contributions made in [3] and [14]. For example, bringing the latency incurred at relays to only 100 ns [3] is already a hard work. And showing that full duplex relays can work with existing WiFi system have already inspired many other works.

More generally, this paper does **not** contradict any other works utilizing full duplex relays. This paper focus only on full duplex relays that try to achieve constructive and destructive addition at the receiver. Yet we think two limitations of full duplex relays may worth noticing when designing systems with them:

- 1) The inevitable extra latency at relays may make the relayed signal arrive later than the direct link at receivers (Obs. 3.5).
- 2) Relays cannot predict future samples that are going to be transmitted, making operations like precoding unlikely to apply at relays.

6 POSSIBLE REMEDIES

From the above analysis and experimental results, we can see that there are stringent requirements on the latency of the relay path to achieve constructive and destructive relaying. In this section, we discuss some possible ways to make favorable conditions for the system. However, how these solutions perform in reality entails more careful investigations and experiments, which is out of the scope of this paper.

Lower sampling rate: Since τ is in the unit of sample time, the system is expected to work better with narrow band signals. For example, the bandwidth of IEEE 802.15.4 is 2 MHz, therefore, the relay will have more time for processing and forwarding the signal compared with wide band signals like WiFi.

Minimize latency at the relay: Oversampling may be used to minimize the latency incurred at the relay. Oversampling has already been used in many full duplex relay based systems for faster response [3, 20]. Alternatively, we may realize full duplex relays with only analog components [1, 16] to eliminate the delays by ADC, DAC, etc. However, the residual self interference at the relay may affect the system performance due to the lack of digital self interference cancellations.

Repeat transmissions: The source node may transmit the same packet more than once (e.g., retransmissions). In this case, the relays can do constructive or destructive relaying to the repeated transmissions. Note that the repetition can also be configured to be symbol level, instead of packet level. Specifically, each symbol is transmitted more than once back to back. In this case, the repeated symbols may be boosted or nullified using the first symbol.

Target non-line-of-sight (NLoS) paths: Based on Claim 3.4, partial constructive or destructive relaying may be achieved by targeting only the NLoS paths. The timing requirement is less stringent as the relayed signal may arrive earlier than signals from NLoS paths in the direct link. Decent performance is expected especially when the LoS path in the direct link is weak or absent while the NLoS paths are strong.

Target a subset of subcarriers: As mentioned in Sec. 3.3, power redistribution across subcarriers will be observed if the relayed signal arrives too late. Instead of targeting all subcarriers, a subset of subcarriers can be boosted or nullified by controlling the delay/phase of the relayed signal. This may be helpful in practice to combat channel selective fading of the direct link.

Figure 7: A transmits a low power signal followed by a strong copy with some latency. R can decode the low power signal and nullify the strong signal at B.

Deliver information to the relay first: If the relay was able to know the packet beforehand, then it is easy to achieve constructive and destructive relaying as the system reduces to the beamforming. One trivial way is to first transmit the packet to the relay, however, this method consumes additional wireless resource (e.g., time, frequency).

To take advantage of the full duplex capability, the data can be delivered to the relay at real time. As shown in Fig. 7, the source node A transmits two copies the signal: a low

power one (dashed blue line) followed by a strong power copy (solid red line) with some latency. Upon receiving the low power signal, the relay R can decode the symbols. By proper interference cancellation (e.g., [12, 30]), the relay can cancel the strong signal with the decoded symbols. As a result, R can continue to decode the low power signal. At the same time, R can forward the decoded symbols such that it boost or nullify the strong signal in the direct link. A similar idea has been explored in [13]. The limitation of the method is that the source node needs to be collaborative and modified. Also, since the low power signal in the direct link is intact, it may cause interference to B depending on the topology.

Figure 8: A diamond relay network. A transmits to C (not shown) via full duplex relay R_1 , but causing interference at B. R_2 could nullify this interference.

Enlarge delay of the direct link: Another line of thinking is to try enlarge delay of the direct link, so the relative latency τ is small or even negative.

We consider a diamond relay network as illustrated in Fig. 8. Node A wants to communicate with node C (not shown) with the help of full duplex relay R_1 , but R_1 causes interference at B at the same time. The destructive full duplex relay R_2 ³ can properly change the signal such that signals destructively combine at node B. Note that the we can control the latency introduced at both relays such that the relative delay τ is small enough. Cooperation among relays is needed to set the filter and power amplification.

7 RELATED WORK

Full duplex. By cancelling the self interference, a full duplex capable node can transmit and receive simultaneously in the same frequency band. Full duplex systems have been well researched and successfully implemented in recent years. Specifically, techniques including antenna, analog and digital cancellations have been explored [9, 11, 15]. A one-antenna design is proposed in [5] by applying a circuit at the antenna end, making full duplex more appealing. [2, 4] show the feasibility of MIMO full duplex. The authors in [8] enable

³We assume R_1 and R_2 are in different collision domains for simplicity. [8] may be used for single collision domain case but requiring further investigations.

end-to-end full duplex communications via full duplex relay clusters. [10] investigates full duplex broadcasting for vehicular networks.

Full duplex relays. Full duplex capable relays have also been explored in many recent works. Full duplex relays can amplify and forward the received samples after receiving them with very small latency. For example, [20] used full duplex relay as privacy protector against wireless sensing, by obfuscating signal features using the relayed signals. [1] shows feasibility of 60 GHz full duplex, and is used to enable untethered virtual reality. [16] mounted full duplex relays to drones to read remote RFID tags. Full duplex relays have also been used as an attack method. For example, masking link signatures [26], controlling and predicting channel values between nodes [19], etc. Analog-only full duplex relays have been explored in [1, 16]. Coexistence of multiple full duplex relays is investigated in [7, 8]. Specifically, [8] enables end-to-end full duplex by employing multiple hops of full duplex relays. A delay-and-forward full duplex relay is proposed in [13], which also tries to boost the received signal power with the help of a full duplex relay, but the solution requires modifications of the receiver. Our paper does not contradict these systems or other full duplex relay based systems.

Constructive and destructive addition. Another method to boost the signal power or nullify signals at specific locations is beamforming, which has been used in protocols like multiuser MIMO and network MIMO [21, 24, 29]. For example, JBM [21] uses the Ethernet backbone to share the down-link packets among access points to achieve joint multi-user beamforming. It must be noted that there is one fundamental difference for the full duplex relay case compared with these protocols: full duplex relays are unaware of the samples being transmitted *beforehand*. In other words, relays get to know each sample at real time while the source node is transmitting.

Cooperative relaying. Cooperative communications with relays have been widely investigated in literature. For example, the authors in [17] use a distributed Alamouti space-time block code to achieve cooperative relaying. [28] evaluates both single-relay and multi-relay cases for cooperative transmissions. However, most of these works consider only half duplex relays. In this paper, we analyze the conditions under which constructive or destructive relaying is possible for full duplex relays.

8 CONCLUSION

In this paper, we provide detailed analysis on latency requirements of the relay link to realize constructive and destructive full duplex relaying. Our analysis and experimental results challenge previous assumptions that CP length is the timing

constraint for OFDM signals to achieve constructive and destructive relaying. We find that constructive and destructive relaying can not be achieved if the relayed signal arrives later than the last tap of the direct link channel. We also discussed achievable facts and their corresponding required conditions. We think that our paper is helpful in understanding limitations of full duplex relays and may stimulate more useful discussions.

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